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Breaking through the attentional window: Capture by abrupt onsets versus color singletons

Nicholas Gaspelin and Eric Ruthruff

University of New Mexico

Mei-Ching Lien

Oregon State University

Kyunghun Jung

University of New Mexico

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Address Correspondence to:

Nicholas Gaspelin
Department of Psychology
1 University of New Mexico
MSC03 2220
Albuquerque, NM 87131-1161
+1 563-340-2053
gaspelin@unm.edu

Abstract

Theeuwes (2004) proposed that stimulus-driven capture occurs primarily for salient stimuli that fall within the observer's attentional window, such as when performing a parallel search. This proposal, supported by some studies, can explain many seemingly discrepant results in the literature. The present study tested this proposal using a modified pre-cuing paradigm. Search mode was manipulated via target-distractor similarity in color space. In the parallel search condition, the orange target "popped out" from a set of distantly colored distractors (blue and green). In the serial search condition, the orange target was more difficult to find amongst a set of similarly colored distractors (yellow and red). In Experiments 1 and 2, cue validity effects for irrelevant color singleton cues were greater under parallel search than serial search, at least partially replicating previous studies favoring the attentional window account (e.g., Belopolsky et al., 2007). We found the opposite pattern, however, for capture by abrupt onsets (Experiments 3 and 4). Here, capture effects were actually greater under serial search. In sum, parallel search appears to facilitate capture by color singletons, yet inhibit capture by abrupt onsets.

Keywords: attentional capture, visual search, spatial attention

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Sometimes, task-irrelevant information draws our attention. While driving, for example, a bright billboard advertisement might draw attention, seemingly against our will. At other times, very salient information fails to capture our attention. A waving pedestrian (or, classically, a waving gorilla) may go unnoticed (Simons & Chabris, 1999). Indeed, one might wonder how a person distracted by every salient stimulus (e.g., flashing police beacons, brake lights, blinking crosswalk signs, neon traffic cones) could possibly survive a single trip to the grocery store. These simple observations raise the question of how involuntary shifts of attention are guided. Can certain "super" stimuli capture our attention at any moment (bottom-up)? Or are these shifts involuntary yet, counterintuitively, driven by what we are looking for (top-down)?

Research on attention capture has made great strides in identifying laboratory scenarios in which salient stimuli do and do not capture attention. However, opinions are still sharply divided about how to reconcile the puzzling empirical discrepancies from different paradigms and different types of salient stimuli. Theeuwes (2004; 2010) has proposed one promising reconciliation in which stimulus-driven capture occurs only when objects are searched in parallel. This claim, if correct, would have important theoretical implications as well as important practical implications for identifying real-world scenarios that leave an operator vulnerable to irrelevant capture. Although there are several suggestive findings (e.g., Belopolsky, Zwaan, Theeuwes, & Kramer 2007; Schreij, Owens, & Theeuwes, 2008; Schreij, Theeuwes, & Olivers, 2010), this claim has not yet been thoroughly tested. In this paper, therefore, we used a pre-cuing paradigm to assess whether differences between search modes (parallel vs. serial) can actually explain the discrepant findings in the attentional capture literature. Before describing the specifics of our approach, we will first review previous evidence for capture by salient objects and the role of search mode.

Stimulus-Driven vs. Goal-Driven Capture of Attention

Stimulus-driven accounts of attentional capture propose that certain salient stimulus features guide attention, irrespective of current goals. Feature singletons, stimuli with a unique feature against a homogenously-featured background, are thought to be particularly salient and are considered likely candidates for stimulus-driven capture. A lone green letter amongst several red letters, for example, would be a color singleton, as would a lone yellow daisy in a field of green grass. Abruptly appearing stimuli (called *abrupt onsets*) and moving stimuli are also thought to be particularly salient.

One of the most prominent variants of stimulus-driven capture is that proposed by Theeuwes (1992, 2004, 2010) based on a zoom-lens model of spatial attention. To briefly summarize, zoom-lens theories assume that the spotlight of spatial attention (often called the *attentional window*) can change in size, focusing either narrowly or diffusely across a visual scene. Theeuwes proposes that relative salience within this attentional window guides subsequent focusing. In other words, any salient stimulus appearing inside the attentional window would subsequently capture attention, whereas those falling outside the window would not. The more diffuse the attentional window (as in parallel search), the more likely a salient stimulus will fall within that window and thus capture attention. Because the size of the attentional window is under voluntary control, a participant could effectively avoid capture by shrinking their attentional window (as in serial search). Thus, search mode strongly determines whether salient stimuli capture attention involuntarily.

Theeuwes (1992) provided initial support for this claim using a paradigm that explicitly encouraged a diffuse attentional window. In this *additional singleton paradigm*, participants searched an array of items for a singleton target, such as a diamond target amongst circle distractors. Because the singleton target "popped out" of the display, it was assumed that participants would search the displays in parallel with a diffuse attentional window. Meanwhile, a task-irrelevant color singleton distractor was sometimes presented. Although participants were instructed to ignore this color singleton distractor, they often produced longer response times (RTs) when it was present than when it was absent. This *present-absent cost* was taken as evidence that the distractor captured attention, temporarily drawing attention away from the target.

Recently, Belopolsky et al. (2007) provided even more direct support for the attentional window account using a go/no-go paradigm (for a related study, see also Belopolsky & Theeuwes, 2010). In this paradigm, participants searched triangular arrays of letters for a target. In the *diffuse* window condition, participants first identified the orientation of the triangular array. If the triangular search array pointed upward, the participant searched the array of letters for the target (go trial). If the triangular search array pointed downward, the participant skipped to the next trial (no-go trial). Presumably, participants spread their attentional window across the entire search display to ascertain which way the large triangular array was pointing. In the *focused* window condition, participants used the shape of the small triangular fixation point, located at screen center, to determine whether the current trial was a go or no-go trial. Presumably, this encouraged a very narrow attentional window. In both of these search conditions, a non-predictive color singleton appeared on every trial at either a target (valid) or distractor (invalid) location. The critical finding was that participants showed validity effects, indicating capture, only under the diffuse window condition. This pattern was taken to support Theeuwes' attentional window account of capture.

Unlike stimulus-driven accounts, goal-driven accounts of attentional capture claim that involuntary shifts depend on what the participant is looking for – the *contingent involuntary orienting hypothesis* (e.g., Folk, Remington, & Johnston, 1992). According to this theory, participants establish an attentional goal (often called an *attentional set*) for the feature distinguishing the target from the rest of the display. If a stimulus matches this attentional set, it will capture attention. In sum, top-down control settings determine attentional capture.

In a classic experiment, Folk et al. (1992) provided evidence for their theory using a pre-cuing paradigm. Participants searched for either an abruptly onsetting target or a red target, in different blocks of trials. This search display was preceded by a non-predictive cue that was either an abrupt onset or red. The cue location could be invalid (different than the target), valid (same as the target), or neutral (when the cue is absent). Also, it could either match or mismatch the distinguishing feature of the target (red or onset). If attention is captured by cues, target responses should be faster for valid cues and slower for invalid cues (called *cue validity effects*). Critically, participants showed cue validity effects only for cues matching the target feature. For example, onset cues produced cue validity effects only when participants looked for onset targets, not red singleton targets. These results suggest that attentional capture, although rapid, stimulus-triggered and apparently involuntary, is nevertheless entirely contingent on the viewer's top-down goals.

The debate between these two competing theories of attentional capture has not yet been resolved. As a reconciliation, stimulus-driven theorists argue that pre-cuing paradigms discourage capture, by encouraging a focused, serial search (Theeuwes, 2004). This hypothesis is quite plausible. When participants search serially, attentional allocation might be primarily determined by proximity from the previous locus of attention (or a fixed search path) rather than salience. Or perhaps slower searches allow more time for top-down task relevance to overcome bottom-up salience. Although highly promising, this attentional window hypothesis has not yet been thoroughly tested, especially in the pre-cuing paradigm, which is the purpose of the present study. Before describing our approach, it will be helpful to first review what exactly is meant by “serial” and “parallel” search.

Parallel versus Serial Search

Treisman and Gelade's (1980) Feature-Integration Theory of attention prominently distinguished parallel and serial processes in visual search. These researchers noted that targets defined by a single feature seem to “pop out” of the search display (called *feature search*). For example, a lone blue letter would certainly stand out in a display of red Ts and green Xs. In such displays, participants are often able to rapidly report the presence or absence of a target, independent of display setsize. These researchers claimed that, in feature searches, all locations are searched in parallel.

Targets defined by a conjunction of features (called *conjunction search*) are considerably more difficult to find. Referring to the previous example, a green T would not stand out in a display containing red Ts and green Xs. Here, the time required to report the presence or absence of a target increases sharply with increasing display setsize (this RT by setsize function is often called the *search slope*). Moreover, search slopes are often roughly twice as steep on absent trials than on target present trials. This finding is exactly what one would expect from a serial, self-terminating search because, on average, only half of the items are searched when the target is present but all are searched when the target is absent. Treisman and Gelade (1980) reasoned that, in conjunction searches, each potential target location is searched serially. They also claimed that search slopes could be used to distinguish parallel and serial search modes from one another. For parallel searches, increasing setsize minimally increases RT (i.e., flat search slope). For serial searches, however, increasing setsize strongly increases RT (i.e., steep search slope), usually in a roughly linear fashion.

Some researchers have criticized the strict parallel-serial search mode distinction and have suggested instead emphasizing degree of efficiency (described further in the Parallel vs. Serial Revisited section in the General Discussion). Although we are sympathetic to these positions, we assume here that the conditions commonly referred to as parallel and serial do in fact reflect very different ways of allocating attention, as required by Theeuwes's (1991; 2004; 2010) reconciliation of the capture literature.

The Present Study

Theeuwes' hypothesis that capture occurs only under parallel search is plausible and consistent with several studies. At the same time, the supporting studies have a few major shortcomings. Many of these studies have exclusively relied on modified versions of Theeuwes' additional singleton paradigm (e.g., Theeuwes, 1992, 1994). Thus, it is unclear whether results from this additional singleton paradigm generalize to other paradigms, such as the pre-cuing paradigm typically employed by goal-driven theorists. Of particular concern is that the present-absent costs typically used in Theeuwes' additional singleton paradigm may reflect non-spatial filtering costs (Becker, 2007; Folk & Remington, 1998) -- a slower decision about where to move attention -- rather than an actual shift of spatial attention. In contrast, cue validity effects in the pre-cuing paradigm are a direct indication of actual shifts of spatial attention (Folk & Remington, 2010).

Another major limitation of these previous studies is that they have exclusively examined capture by color singletons (e.g., Belopolsky & Theeuwes, 2010; Belopolsky et al., 2007; Theeuwes, 1992). It is critical to establish whether the attentional window account generalizes to all salient stimuli. Here, we distinguish between a strong and weak version of the attentional window account. The strong version of the attentional window theory is a fundamental assumption about the nature of attentional capture, making no distinction between color singletons and onsets (e.g., Theeuwes, 1991; 1992; 2004). This seems to be what attentional window theorists initially had mind. For example, Theeuwes (1991) states, "…in an unfocused state, attention covers the entire visual field, which suggests that abrupt onsets and offsets do attract attention similarly. When an endogenous cue enables one to 'zoom in' on a particular area, abrupt transients clearly outside the circumscribed area cease to attract attention" (p. 90). However, a weak version adds an amendment that parallel search is needed for color singletons, but not abrupt onsets. This weak version has been adopted in more recent studies (e.g., Belopolsky et al., 2007; Theeuwes, 2010).

To our knowledge, no researchers have explicitly assessed the effect of search mode on capture by abrupt onsets. So, it is unclear whether the strong or weak version of attentional window theory is correct. Many studies indirectly suggest that abrupt onsets can capture attention even under serial search (Franconeri, Hollingworth, & Simons, 2005; Franconeri & Simons, 2003; Jonides & Yantis, 1988; Lamy & Egeth, 2003; Rauschenberger, 2003; Schreij et al., 2008, 2010), but did not actually manipulate search mode or verify that a particular search mode was used. To resolve this issue, further experiments are needed.

In the present study, we tested whether parallel search enables capture by irrelevant salient stimuli in a pre-cuing paradigm akin to that used by Folk et al. (1992). Using a single manipulation of search mode, we examined capture by color singletons (Experiments 1 and 2) and by abrupt onsets (Experiments 3 and 4). In Experiment 5, we removed the cue entirely to verify that our manipulation of search mode was effective.

Experiment 1

In the present pre-cuing task, participants searched an eight item array for an orange target letter and reported its identity (T or L); see Figure 1. We manipulated search mode via distractor similarity with respect to the orange target letter. In our "parallel" search condition, distractor colors (green and blue) were very far in color space from the orange target letter. In this condition, the target is highly salient and will "pop out" of the display. In our "serial" search condition, distractor colors (red and yellow) were very close in color space to the target letter. Half of participants were assigned to the parallel condition and the other half were assigned to the serial condition. Before the search array, a color singleton cued a potential target location. This color singleton pre-cue could either match (relevant) or mismatch (irrelevant) the target color. When present, this cue was non-predictive of target location (invalid on 7/8^{ths} of trials and valid on 1/8th of trials).

If capture occurs only under parallel search, then cue validity effects (defined as invalid RT minus valid RT) should occur for irrelevant color singleton cues only in the parallel search condition, but not the serial search condition. However, contingent capture theory would predict negligible cue validity effects by irrelevant color singleton cues in either search condition.

<u>Methods</u>

Participants. Forty-eight undergraduates from the University of New Mexico participated for course credit. Two participants in the serial search condition were excluded from the final data analysis because of unusually high error rates (>20%). This meant that 22 participants were analyzed in the serial condition and 24 in the parallel condition. All participants in all experiments of this study had normal color vision as assessed by the Ishihara color vision test and self-reported normal or corrected-to-normal visual acuity.

Apparatus. A Dell personal computer displayed stimuli on 19-inch CRT monitors.

Stimuli. E-Prime software was used to design and present stimuli. Stimuli were the letters T and L in Arial font. These letters were either green (RGB value of 0, 153, 0), red (255, 0, 0) blue (40, 40, 255), yellow (255, 205, 0), orange (255, 130, 0), or white (255, 255, 255), designed to be of roughly equal luminance on a black background. The letters were 1.9^{o} in width and height, based on an average viewing distance of 60 cm. Placeholders were white unfilled boxes 2.4^{o} in width and height. There were nine placeholders (eight around the potential target locations and one at fixation). These placeholders defined an imaginary rectangle 12.4^{o} in width and height. In the cue frame, one of the placeholder boxes served as a cue and could be green, red, blue, yellow, or orange (same RGB values as those used for the letters in the target display); the remaining boxes were white.

Design. Each search display contained four Ts and four Ls (see Figure 1). The orange target letter's identity (T or L) was chosen at random. Display type (serial or parallel) was varied between participants. For parallel search arrays, distractors consisted of three green, three blue, and one white letter. For serial search arrays, distractors consisted of three yellow, three red, and one white letter. Color singleton pre-cues were present on all trials and were non-predictive of target location. The pre-cue was valid on 1/8th of trials and invalid on 7/8th of trials. The color of the cue was either the same as the target (i.e., orange; one-third of trials) or different (blue, green, yellow, red; two-thirds of trials). Each participant first performed 72 practice trials divided into 2 block, then 576 trials divided into 8 blocks.

Procedure. Participants were instructed to search for an orange L or T and to respond as quickly and accurately as possible by pressing the key labeled “L” or “T” (actual keys: “c” or “b”). Participants were also instructed that the pre-cue was non-predictive of the target location and should be ignored. Each trial began with a presentation of the nine placeholders for 1000 ms. This was followed by a blink of the central fixation placeholder for 100 ms. Then the color singleton pre-cue display appeared for 100 ms, followed by another presentation of the placeholders for 50 ms. The search array then appeared for 500 ms or until the participant made a response. Participants were given immediate accuracy feedback for 100 ms (a high tone for incorrect responses, no sound for correct responses). Participants also received block-by-block feedback on their mean RT and accuracy.

<u>Results & Discussion</u>

Trials with RTs greater than 2000 ms or less than 200 ms (0.7 % of trials) were excluded from RT and error rate analyses. Trials with an incorrect response were also excluded from RT analyses. The resulting mean RTs and error rates are shown in Table 1. Cue validity effects by condition are shown in Figure 2.

A three-way analysis of variance (ANOVA) was conducted on mean RTs with the factors search condition (parallel vs. serial; between subjects), cue validity (invalid vs. valid; within subjects) and cue color (relevant vs. irrelevant; within subjects). This analysis revealed faster responses in the parallel condition (521 ms) than the serial condition (663 ms), $F(1, 44) = 44.632$, $p < .001$, $\eta^2 = .504$. This large effect suggests that our manipulation of search mode was effective.

Participants generally responded more slowly to the target following invalid cues (614 ms) than valid cues (570 ms), $F(1, 44) = 100.942$, $p < .001$, $\eta^2 = .696$. These overall cue validity effects did not differ between search conditions, $F(1, 44) = .090$, $p > .10$, $\eta^2 = .002$. Participants responded slightly faster on trials where the color singleton cue was relevant (586 ms) than when it was irrelevant (598 ms), $F(1, 44) = 25.845$, $p < .001$, $\eta^2 = .370$. Participants were slowed more by singleton cues under serial search (18 ms) than parallel search (7 ms), $F(1, 44) = 5.241$, $p < .05$, $\eta^2 = .106$.

The 3-way interaction of search condition by cue validity by cue color was significant, $F(1, 44) = 9.256$, $p < .01$, $\eta^2 = .174$. We followed up this interaction with an investigation of simple main effects. Cue validity effects were greater for relevant color singletons (70 ms) than for irrelevant color singletons (18 ms), $F(1, 44) = 95.282$, $p < .001$, $\eta^2 = .694$. Pre-planned t-tests revealed that cue validity effects from <u>relevant</u> color singletons did not differ significantly between search conditions (63 ms for parallel and 77 ms for serial), suggesting that goal-driven capture was not affected by search mode, $t(44) = 1.17$, $p > .10$.

The key question in this experiment was whether capture by <u>irrelevant</u> color singletons cues would be greater in the parallel search conditions. Cue validity effects for irrelevant color singletons were in fact significantly greater under parallel search (27 ms) than serial search (9 ms), $t(44) = 2.18$, $p < .05$. Pre-planned follow-up tests revealed that cue validity effects were significant only under parallel search, $t(23) = 6.06$, $p < .001$, not serial search, $t(21) = 1.12$, $p > .10$ (see Table 1).

The same three-way mixed design ANOVA was conducted on mean error rates. Participants made significantly more errors following invalid cues (9.9%) than valid cues (7.6%), $F(1, 44) = 18.378$, $p < .001$, $\eta^2 = .295$. These cue validity effects on error rates were greater for relevant cues (3.7%) than irrelevant color cues (1.0%), $F(1, 44) = 7.204$, $p = .01$, $\eta^2 = .141$. All other interactions and main effects were not significant.

To summarize, this experiment tested whether capture is greater under parallel search than serial search. Participants generally responded much more slowly in the serial than the parallel search condition, suggesting that our manipulation of search mode was effective. Relevant color singleton cues (i.e., orange) produced large cue validity effects that did not vary much between search modes. However, irrelevant color singletons produced larger cue validity effects under parallel search than serial search, replicating previous findings with color singletons (Belopolsky et al., 2007).

Experiment 2

In Experiment 1, we found that capture by irrelevant color singletons was greater under parallel search with a setsize of eight. However, pre-cuing paradigms typically use smaller setsizes (e.g., setsize of 4 in Folk et al., 1992). In an attempt to more closely replicate such experiments, we reduced the setsize to four in this experiment.

Methods

Participants. Fifty-eight new participants, drawn from the same participant pool as in Experiment 1, were in this experiment. Five participants were excluded from the final analysis because of an unusually high error rate (more than 20%). As a result, 25 participants in the serial condition and 28 in the parallel condition were included in the final analysis.

Apparatus, stimuli and procedure. The methods and stimuli were the same as Experiment 1, except that the setsize was reduced from 8 to 4. There were now five placeholders (four around the potential target locations and one around the fixation location). These placeholders were arranged in square formation that was 10^{o} in width and height. The cue was presented on only half of the trials, because cue rarity is believed to encourage attentional capture (Neo & Chua, 2006). When present, the cue was again non-predictive of search location (25% valid and 75% invalid).

Results & Discussion

The data analysis was similar to that of Experiment 1. Application of the RT cutoffs (less than 200 or greater than 2000 ms) eliminated 0.3% of trials. The resulting mean RTs and error rates are shown in Table 2. Cue validity effects by condition are shown in Figure 2.

First, to assess the search slopes of our search conditions, we compared the data from Experiment 1 (setsize 8) and Experiment 2 (setsize 4) collapsed across cue validity conditions. These data were analyzed with a two-way ANOVA with the between-subject factors setsize (4 vs. 8) and search condition (parallel vs. serial). Participants responded more quickly in the parallel condition (540 ms) than the serial condition (624 ms), $F(1, 95) = 37.388$, $p < .001$, $\eta^2 = .282$. Participants also responded more quickly at setsize 4 (556 ms) than setsize 8 (606 ms), $F(1, 95) = 13.292$, $p < .001$, $\eta^2 = .123$. Critically, the interaction between setsize and search condition was significant, with participants producing steeper search slopes in the serial condition (26.4 ms) than the parallel condition (-1.1 ms), $F(1, 95) = 15.679$, $p < .001$, $\eta^2 = .143$. This classic interaction suggests that our manipulation of search mode was effective (see also Experiment 5).

A three-way ANOVA was conducted on mean RTs from Experiment 2 with the factors search condition (parallel vs. serial; between subjects), cue validity (invalid vs. valid; within subjects) and cue color (relevant vs. irrelevant; within subjects). There was a trend for participants to respond more quickly in the parallel condition (537 ms) than the serial condition (567 ms), although this difference did not reach significance, $F(1, 51) = 2.567$, $p > .10$, $\eta^2 = .048$. This lack of significance reflects smaller effects of search condition at smaller setsizes and hence less power (note that Experiments 1 produced highly significant effects at larger setsizes; see also Experiment 3 below). Moreover, various interactions with search mode were significant, indicating that the search manipulation did, in fact, influence spatial attention.

Participants responded slightly more slowly on trials where the singleton cue was an irrelevant color (554 ms) rather than a relevant color (549 ms), $F(1, 51) = 3.943$, $p < .06$, $\eta^2 = .072$. The interaction of search condition and cue color was also significant, $F(1, 51) = 4.064$, $p < .05$, $\eta^2 = .074$. A follow-up analysis revealed slower responses with irrelevant cues (572 ms) than with relevant cues (561 ms) under serial search $t(24) = 3.08$, $p < .01$. However, response times were similar with irrelevant cues (537 ms) and relevant cues (537 ms) under parallel search, $t(27) = .02$, $p > .10$.

Participants responded more slowly on invalid trials (569 ms) than valid trials (535 ms), $F(1, 51) = 74.813$, $p < .001$, $\eta^2 = .595$. As in Experiment 1, cue validity effects were greater for relevant color singletons (53 ms) than for irrelevant color singletons (16 ms), $F(1, 51) = 43.497$, $p < .001$, $\eta^2 = .46$. Overall, participants did not show significantly greater cue validity effects under parallel search (36 ms) than under serial search (33 ms), $F(1, 51) = .100$, $p > .10$, $\eta^2 = .002$. Note, this effect is of little interest because it is pooled across relevant and irrelevant cues, whereas we are primarily interested in the effects of irrelevant cues alone (see below).

The 3-way interaction of search condition by cue validity by cue color was significant, $F(1, 51) = 5.009$, $p < .05$, $\eta^2 = .089$. This indicated that validity effects by irrelevant cues are dependent on search mode, while validity effects by relevant cues did not depend on search mode. We followed up this interaction with an investigation of simple main effects. Pre-planned t-tests revealed that cue validity effects for <u>relevant</u> colors were not greater under parallel search (48 ms) than serial search (57 ms), $t(51) = .819$, $p > .10$. This finding suggests that relevant color singleton cues capture attention strongly regardless of search mode.

The main question in this experiment is whether capture by irrelevant color singletons is greater under parallel search, even at the smaller setsizes typically used in pre-cuing paradigms. Indeed, cue validity effects for irrelevant color singletons were again greater under parallel search (24 ms) than serial search (9 ms), $t(51) = 2.238$, $p < .05$. Cue validity effects were significant under parallel search, $t(27) = 5.86$, $p < .001$, but not serial search, $t(24) = 1.646$, $p > .10$. These data replicated results in Experiment 1 with setsize 8 and suggest that irrelevant color singletons can capture attention only under parallel search in the pre-cuing paradigm.

A three-way mixed design ANOVA was also conducted on mean error rates with the factors search condition (parallel vs. serial; between subjects), cue validity (invalid vs. valid; within subjects) and cue color (relevant vs. irrelevant; within subjects). Participants performed more accurately on invalid trials (8.6%) than valid trials (7.2%), $F(1, 51) = 5.270$, $p < .05$, $\eta^2 = .094$. These cue validity effects on error rates were greater for relevant color singletons (2.6%) than irrelevant color singletons (0.5%), $F(1, 51) = 5.185$ $p < .05$, $\eta^2 = .092$. All other main effects and interactions were nonsignificant.

To summarize, we replicated the main finding of Experiment 1 – that task-irrelevant color singletons captured attention only under parallel search – using a smaller setsize of four items. Both Experiments 1 and 2 generally support the claim that capture by task-irrelevant color singletons is possible only under parallel search (Belopolsky & Theeuwes, 2010; Belopolsky et al., 2007; Theeuwes, 2004).

Experiment 3

In Experiments 1 and 2, we found capture by irrelevant color singletons only in the parallel search condition. However, it is unclear whether these results generalize to other types of salient stimuli. In Experiment 3, we examined capture by perhaps the most widely studied type of salient stimulus - abrupt onsets.

Methods

Participants. Sixty-one new participants from University of New Mexico participated in this experiment. Three participants were excluded from analysis because of an unusually high error rate (more than 20%).

Apparatus, stimuli and procedure. The methods were mostly the same as in Experiments 1 and 2, except that white abrupt onset cues were used instead of color cues (a change in the color of a box). Onset cues consisted of four white circles ($.5^{o}$ in diameter) surrounding one of the rectangular placeholders in the cue display (forming an imaginary diamond that was 3.3^{o} in height and width). The rectangular placeholders were white in Experiments 1 and 2 but were changed to gray (RGB value: 138, 138, 138) in this experiment to make the white onset dots more distinct. In order to discourage attentional set for onsets, we used pre-masks to make the search array consist entirely of offsets. The pre-masks were white rectangles with a central vertical line (whose segments could be deleted to reveal a T or L). These masks appeared during the fixation and cue displays. Similarly, the blink previously denoting the beginning of a trial was also removed to remove any incentive to establish an attentional set for abrupt onsets.

Search array setsize (4 or 8) was varied trial-by-trial. Every display had nine placeholders (two on each side and one in the center; see Figure 3). In the setsize 4 conditions, search array letters were spaced evenly across the entire display of 8 locations, with each letter having an empty placeholder between it and another letter. The location of these four letters varied randomly across trials.

To increase statistical power, search display type (parallel vs. serial) was varied within participants. To reduce carryover effects, the experiment was divided into two session halves, one for each search condition; condition order was counterbalanced across participants. During each session half, participants performed a practice block of 36 trials followed by 5 blocks of 72 trials (360 total).

Results & Discussion

The data analysis was similar to that of Experiments 1 and 2. Application of the RT cutoffs (200 to 2000 ms) eliminated 0.6% of trials from RT and error rate analyses. Trials with an incorrect response were also excluded from RT analyses. The resulting mean RTs and error rates are shown in Table 3. Cue validity effects by condition are shown in Figure 4.

First, we tested whether our manipulation of search mode was successful. For cue absent trials, we conducted a two-way ANOVA on mean RTs with two factors: search condition (parallel vs. serial) and setsize (4 vs. 8). Participants generally responded faster in the parallel condition (569 ms) than the serial condition (671 ms), $F(1, 57) = 168.443$, $p < .001$, $\eta^2 = .747$. Participants also responded faster at setsize 4 (592 ms) than setsize 8 (648 ms), $F(1, 57) = 295.014$, $p < .001$, $\eta^2 = .838$. Most importantly, participants produced steeper search slopes in the serial condition (20.8 ms per item) than the parallel condition (7.5 ms per item), $F(1, 57) = 69.175$, $p < .001$, $\eta^2 = .548$. This classic setsize by search condition interaction on cue absent trials suggests that our manipulation of search mode was in fact successful.

Second, for cue present trials, we conducted a three-way within-subject ANOVA on mean RTs with the factors search condition (parallel vs. serial), cue validity (invalid vs. valid) and setsize (4 vs. 8). Again, participants performed faster in the parallel condition (559 ms) than the serial condition (662 ms), $F(1, 57) = 151.092$, $p < .001$, $\eta^2 = .726$. Participants also responded faster at setsize 4 (586 ms) than setsize 8 (635 ms), $F(1, 57) = 163.757$, $p < .001$, $\eta^2 = .742$. Moreover, participants showed steeper search slopes for the serial condition (18.4 ms per item) than the parallel condition (5.9 ms per item), $F(1, 57) = 63.187$, $p < .001$, $\eta^2 = .526$. This also suggests our manipulation of search strategy was successful.

The data indicate that our task-irrelevant abrupt onset cues captured attention. Participants showed cue validity effects, responding more slowly on invalid trials (630 ms) than valid trials (591 ms), $F(1, 57) = 66.751$, $p < .001$, $\eta^2 = .539$. These cue validity effects were significantly larger at setsize 8 (46 ms) than setsize 4 (32 ms), $F(1, 57) = 6.281$, $p < .05$, $\eta^2 = .099$.

The critical question was whether irrelevant onsets would capture attention only under parallel search. Clearly this was not the case; cue validity effects were not greater under parallel search (34 ms) than serial search (44 ms), $F(1, 57) = 1.994$, $p > .10$, $\eta^2 = .034$. Note that this non-significant trend (larger cue validity effects under the serial condition than the parallel condition) is actually in the wrong direction relative to that predicted by the strong version of Theeuwes' (2004) original attentional window account. Also, the three-way interaction of search condition, setsize, and validity was also non-significant, $F(1, 57) = 1.03$, $p > .10$, $\eta^2 = .018$. Pre-planned t-tests revealed that cue validity effects at each setsize and search condition were significant (see Table 3). Cue validity effects were significant under parallel search at both setsize 4 and 8, $t(57) = 5.40$, $p<.001$ and $t(57) = 6.32$, $p<.001$. Cue validity effects were also significant under serial search at both setsize 4 and 8, $t(57) = 6.49$, $p<.001$ and $t(57) = 5.31$, $p<.001$. Altogether, these results suggest that search mode did not affect capture by abrupt onsets. Instead, a nonsignificant trend suggested that capture may actually be greater under serial search.

The same three-way ANOVA was conducted on mean error rates on cue present trials as well. Participants made more errors in the serial condition (8.2%) than the parallel condition (6.2%), $F(1, 57) = 6.77$, $p < .05$, $\eta^2 = .106$. Participants also made more errors at setsize 8 (8.0%) than setsize 4 (6.5%), $F(1, 57) = 10.439$, $p < .01$, $\eta^2 = .156$. Participants also made more errors on invalid trials (8.0%) than valid trials (6.4%), $F(1, 57) = 12.750$, $p = .001$, $\eta^2 = .183$. Participants also had steeper error rate slopes (akin to search slope) in the serial condition (0.7% per item) than the parallel condition (0.1% per item), $F(1, 57) = 4.78$, $p < .05$, $\eta^2 = .077$. All other interactions were nonsignificant.

Experiments 1 and 2 replicated previous results, showing greater capture effects by color singletons under parallel search (Belopolsky et al., 2007). However, in this experiment, we found, if anything, the opposite effect for task-irrelevant abrupt onsets. The nonsignificant trend went in the wrong direction, hinting that there might be even greater capture under serial than parallel search.

Experiment 4

In Experiment 3, we found no evidence of enhanced capture by onset pre-cues (150-ms cue to target stimulus onset asynchrony [SOA]) under parallel search. Note, however, that many studies demonstrating capture by abrupt onsets present the onset simultaneously with the search array (e.g., Franconeri & Simons, 2003; Jonides & Yantis, 1988). Although we see no obvious reason why this should matter, we wanted to replicate our results under the conditions most commonly studied. In this experiment, therefore, we assessed whether capture by onset cues appearing simultaneous with the search array (0-ms SOA) is enhanced under serial search.

Methods

Participants. A new sample of thirty-nine University of New Mexico students participated for course credit. Two participants were excluded from analysis because of an unusually high error rate (more than 20%).

Apparatus, stimuli and procedure. This experiment was nearly identical to Experiment 3, except that the pre-cue (100 ms) and the intermediate frame (50 ms) were removed. Instead, the onset cue appeared simultaneously with the search display. When present, the onset cue appeared at the target location on 25% of trials (i.e., was non-predictive). Also, setsize was not manipulated; all displays contained only four placeholders and search arrays contained only four letters, as in Experiment 2.

Results & Discussion

The data analysis was similar to that of the previous experiments. Application of the RT cutoffs (200 to 2000 ms) eliminated 0.3% of trials from RT and error rate analyses. The resulting mean RTs and error rates are shown in Table 4. Cue validity effects by condition are shown in Figure 4.

First, we assessed whether our search manipulation was effective on absent-cue trials. A pre-planned t-test revealed that participants did in fact respond more quickly in the parallel condition (532 ms) than the serial condition (586 ms) when the cue was absent, $t(36) = 9.27$, $p < .001$. Second, a two-way within-subject ANOVA was conducted on mean RTs with the factors search condition (parallel vs. serial) and cue validity (invalid vs. valid). Participants were again significantly faster in the parallel search condition (535 ms) than the serial search condition (594 ms), $F(1, 36) = 96.222$, $p < .001$, $\eta^2 = .702$. Participants responded more slowly following invalid onset cues (575 ms) than valid cues (556 ms), $F(1, 36) = 20.11$, $p < .001$, $\eta^2 = .358$, indicating attention capture by onsets.

Again, the main point of this study was to determine whether capture by irrelevant onsets is greater under serial search than parallel search. Participants produced significantly greater cue validity effects under serial search (28 ms) than parallel search (10 ms), $F(1, 36) = 5.494$, $p < .05$, $\eta^2 = .132$, confirming the trend observed in Experiment 3. Pre-planned t-tests revealed that cue validity effects were significant under both parallel and serial conditions, $t(36) = 2.149$, $p < .05$ and $t(36) = 4.321$, $p < .001$.

The same two-way ANOVA was conducted on mean error rates as well. Participants made significantly more errors under serial search (10.1 %) than parallel search (7.9 %), $F(1, 36) = 8.493$, $p = .01$, $\eta^2 = .279$. All other main effects and interactions were nonsignificant.

To summarize, we investigated whether Experiment 3 (which a showed a trend towards greater capture under serial) would replicate even when the irrelevant abrupt onset appears with the search array (0-ms SOA). We once again found stronger cue validity effects by abrupt onsets under serial search than parallel search and this time the trend was statistically significant. In fact, cue validity effects by abrupt onsets were miniscule in the parallel condition (only 9 ms). This finding directly contradicts Theeuwes' attentional window account of capture.

Experiment 5

Experiments 1-4 showed that search mode can significantly influence capture by abrupt onsets and color singletons. We did find the typical steeper search slopes for serial condition than parallel condition in Experiment 3. However, one could argue that the cue appeared on a portion of trials in this experiment, possibly adding noise to the search slopes. In this control experiment, we removed the pre-cue to provide a purer assessment of whether our search mode manipulation was effective.

Participants. A new sample of 25 University of New Mexico students participated for course credit. Two participants were excluded from analysis because of an unusually high error rate (more than 20%). All participants had normal color vision as assessed by the Ishihara color vision test. They also self-reported normal or corrected-to-normal visual acuity.

Apparatus, stimuli and procedure. This experiment was nearly identical to Experiment 3, except that the pre-cue (100 ms) and the intermediate frame (50 ms) were removed. Setsize was manipulated by trial. Again, search display type (parallel vs. serial) was varied within participants. The experiment was divided into two session halves, one for each search condition; order was counterbalanced across participants. During each session half, participants performed a practice block of 36 trials followed by 5 blocks of 72 trials (360 total).

Results & Discussion

The data analysis was similar to that of Experiment 4. Application of the RT cutoffs (200 to 2000 ms) eliminated 0.3% of trials from RT and error rate analyses. The resulting mean RTs and error rates are shown in Table 5.

We conducted a two-way ANOVA on mean RTs with two factors: search condition (parallel vs. serial) and setsize (4 vs. 8). Participants generally responded faster in the parallel condition (524 ms) than the serial condition (599 ms), $F(1, 22) = 56.512$, $p < .001$, $\eta^2 = .72$. Participants were also faster at setsize 4 (534 ms) than setsize 8 (590 ms), $F(1, 22) = 333.603$, $p < .001$, $\eta^2 = .938$. Most importantly, search slopes were more than twice as steep in the serial condition (19.2 ms per item) than the parallel condition (8.7 ms per item), $F(1, 22) = 65.958$, $p <$

.001, $\eta^2 = .75$. This setsize by search condition interaction trials suggests that our manipulation of search mode was in fact successful.

The same ANOVA was applied to mean error rates. Participants generally made slightly more errors at setsize 8 (9.8%) than setsize 4 (8.5%), $F(1,22) = 6.25$, $p < .05$, $\eta^2 = .229$. All other main effects and interactions were nonsignificant.

General Discussion

Researchers currently debate whether purely stimulus-driven attentional capture is possible. While one line of research provides evidence that attentional capture is strictly goal-driven (Atchley, Kramer, & Hillstrom, 2000; Folk & Remington, 1998; Folk et al., 1992, 1994; Gibson & Kelsey, 1998; Lien, Ruthruff, & Cornett, 2010; Lien, Ruthruff, & Johnston, 2010; Lien, Ruthruff, Goodin, & Remington, 2008), another line of research routinely provides evidence of stimulus-driven capture (Belopolsky & Theeuwes, 2010; Belopolsky et al., 2007; Franconeri & Simons, 2003; Theeuwes, 1992, 2004, 2010; Yantis & Jonides, 1984). To reconcile these conflicting results, Theeuwes (1991, 2004, 2010) has proposed that stimulus-driven capture is possible only under parallel search, when participants employ a diffuse attentional window. Perhaps serial search is too slow or too deliberate to be strongly influenced by task-irrelevant salience; for example, the “pull” from salient items might wear off over time, or be ignored when participants choose a scan path in advance. In fact, a few studies have supported this claim with color singletons (Belopolsky & Theeuwes, 2010; Belopolsky et al., 2007; Theeuwes, 1992, 1994). However, the effect of search mode has thus far been demonstrated using a single paradigm (the additional singleton paradigm) with some notable drawbacks and using a narrow range of salient stimuli (always color singletons). Our aim was to determine whether the effect of search mode generalizes to other salient stimuli and paradigms, particularly those that allow a more definitive assessment of whether spatial attention was captured.

In the present experiments, we used a pre-cuing paradigm and manipulated search mode via color space. In Experiment 1, with setsize 8, we found that capture by task-irrelevant color singletons was indeed greater under parallel search (cue validity effect of 27 ms) than serial search (9 ms). In Experiment 2, we replicated these effects at a smaller setsize of 4, typical of the pre-cuing paradigm (e.g., Folk et al., 1992). So, capture by irrelevant color singletons does seem to depend on a parallel search mode.

When we investigated capture by abrupt onsets, however, parallel search mode was not necessary for capture. In Experiment 3, we found no evidence that capture by abrupt onsets was greater under parallel search (cue validity effect 34 ms) than serial search (44 ms). In fact, marginally significant trends in the cue validity effects suggested that capture was promoted under serial search. In Experiment 4, we assessed attentional capture with abrupt onset cues appearing simultaneously with the search display, rather than before (as a pre-cue). Here, we found substantially larger capture effects by abrupt onsets under serial search (28 ms) than parallel search (10 ms).

Altogether, these findings argue against the strong version of the attentional window account, which proposes that a diffuse attentional window (i.e., parallel search) inherently promotes capture by all salient stimuli (e.g., Theeuwes, 1991). Instead, the pattern of results is consistent with a weaker version of the attentional window account, which asserts that abrupt onsets are somehow special (e.g., Belopolsky et al., 2007; Theeuwes, 2010).

Relation to Previous Research

Our finding that capture effects are quite different for color singletons and abrupt onsets has an unanticipated implication for previous studies comparing onsets and color singletons (Franconeri, Hollingworth, & Simons, 2005; Franconeri & Simons, 2003; Jonides & Yantis, 1988). These studies have routinely demonstrated that abrupt onsets (and other dynamic stimuli) are able to capture attention more strongly than color singletons. The catch is that these studies typically use designs that encourage serial search (e.g., Franconeri and Simons, 2003). Our findings suggest that, had the authors instead used displays that encouraged parallel search, the difference in capture might have disappeared.

Our finding of greater capture by irrelevant color singletons under parallel search might be criticized as resulting from singleton detection mode. Bacon and Egeth (1994) argued that participants can use two distinct search modes: a *singleton detection mode*, where participants search broadly for singletons and a *feature search mode*, where participants search for a specific feature (for a recent review, see Egeth, Leonard, & Leber, 2010). Capture, they claim, occurs only under singleton detection mode, when participants have an attentional set for any feature singleton. In the parallel search condition, a singleton detection theorist might claim that we encouraged our participants to use a singleton detection mode and search more generally for color-space singletons.

However, it is unlikely that participants were using singleton detection mode. We took precautions to discourage singleton detection mode by including an additional color-space singleton distractor (a white letter) and two different distractor colors in all displays. Also, participants always showed greater capture for relevant cues than irrelevant cues, even under parallel search. Singleton detection accounts would seem to predict no difference in capture by both either cue type, because both match the presumed goal of a feature singleton. Moreover, the results of Experiments 3 and 4 (with the same task as in Experiments 1 and 2) are entirely inconsistent with singleton-detection mode accounts. Such accounts would naturally predict greater capture for abrupt onsets under parallel search (supposedly encouraging singleton-detection mode) than serial search (supposedly encouraging feature search), yet we observed the opposite data pattern.

Relevance versus Salience

The present data provide evidence that irrelevant salient stimuli can capture attention to some degree, even when they do not resemble the target. But what is more important for attentional capture, relevance or salience? Many experiments demonstrating capture do not include relevant cues. So, Experiments 1 and 2 give us a unique opportunity to compare capture by relevant and irrelevant cues. In these experiments, it is clear that relevant cues captured attention much more strongly. Relevant color cues captured attention regardless of search mode, unlike irrelevant cues. Even under parallel search, the pooled cue validity effects (Table 6) show that the irrelevant cue validity effects (25.7 ms) were only about 47% the size of that produced by relevant orange cues (54.9 ms). This finding casts doubt on attentional window accounts claiming that top-down selectivity disappears under parallel search (Belopolsky et al., 2007). The current data suggest that, at most, top-down selectivity is reduced under parallel search.

Unlike the current study, many previous pre-cuing studies have reported no evidence of capture from irrelevant color singletons (Folk & Remington, 1998; Folk et al., 1992, 1994; Gibson & Kelsey, 1998; Lien, Ruthruff, & Cornett, 2010; Lien, Ruthruff, & Johnston, 2010; Lien, Ruthruff, Goodin, & Remington, 2008). To further investigate this discrepancy, we performed a finer-grained two-way ANOVA with the factors of search condition (parallel vs. serial) and irrelevant cue color (blue/green vs. yellow/red) on the cue validity effects pooled across Experiment 1 and 2. Cue validity effects were greater for parallel conditions (25.7 ms) than serial conditions (8.1 ms), $F(1, 97) = 11.22$, $p = .001$, $\eta^2 = .104$, and greater for yellow/red cues (26.9 ms) than blue/green cues (6.9 ms), $F(1, 97) = 16.82$, $p < .001$, $\eta^2 = .148$. The interaction between these variables was nonsignificant, $F(1, 97) = .347$, $p > .10$, $\eta^2 = .004$. So, capture by irrelevant cues depended strongly on both search mode and similarity of the irrelevant cue color to the target.

One explanation for this pattern of results is that participants slightly broaden their attentional set under parallel search to include irrelevant colors similar to the target color; because the distractors in the target display are never close to the target color, they can afford to do so. On this view, capture by irrelevant color cues would still be goal-driven. But, because there is no independent measure of attentional set in the pre-cuing paradigm, it is difficult to determine exactly what participants were looking for. Note, that such a goal-driven account would have difficulty explaining the small but significant cue validity effects by blue and green cues under parallel search (14.3 ms).

Additional factors may have also increased the probability of capture by salient irrelevant stimuli (color singletons and abrupt onsets) in the present study. For example, large set-sizes (as in Experiment 1 and 3) may enhance the costs and benefits of capture, without necessarily increasing the probability of capture (Yeh & Liao, 2011). Also, abrupt onset cues appeared only on 50% of trials, and there is some evidence that salient stimuli capture attention more effectively when presented rarely (Neo & Chua, 2006), perhaps because there is less incentive to inhibit them.

Parallel versus Serial Search Revisited

Many researchers have pointed out that it is difficult to unambiguously determine whether search is parallel or serial (Moore & Wolfe, 2001; Palmer, 1995; Pashler, 1987; Townsend, 1971, 1976, 1990; Wolfe, 1994, 1998a, 1998b). Although steep and flat search slopes are certainly consistent with serial and parallel distinctions, respectively, alternative explanations are logically tenable. For example, typical linearly increasing search slopes indicative of serial search could be a result of a limited capacity parallel search (Mordkoff & Yantis, 1993; Townsend, 1971, 1976, 1990) or decision noise (Palmer, 1995; Palmer, Verghese, & Pavel, 2000). Indeed, actual data do not necessarily reveal a dichotomous distinction between serial and parallel search slopes (Wolfe, 1998b).

Regardless of the above criticisms, the current experiments were designed to test Theeuwes' attentional window account, which presumes the existence of two different search modes. Even if one assumes that no distinct search modes exist, the present data still show that making search more difficult (i.e., "more serial" or "less efficient") can strongly influence attentional capture, and therefore deserves more study.

Concluding Remarks

Previous researchers have argued that capture occurs only under parallel search with a diffuse attentional window (Theeuwes, 2004). For example, a bright billboard might capture attention only when we are searching a scene in parallel for potential hazards, but not when serially searching signs for a particular street name. Previous studies have supported this proposition for the case of color singletons, often using the additional singleton paradigm (e.g., Theeuwes, 1992, 1994). However, these studies did not examine other types of salient stimuli, such as abrupt onsets, or use more alternative paradigms that can more reliably measure shifts of spatial attention.

We investigated this issue using a pre-cuing paradigm, with easy and difficult searches (intended to encourage parallel and serial search, respectively). For color singletons, we demonstrated greater effects of capture under parallel search than serial search. However, unlike previous studies showing this effect, the capture effects here were confirmed using a reliable indicator of the capture of spatial attention - cue validity effects. Nevertheless, we found the opposite pattern of results when we examined capture by abrupt onsets: capture effects were actually greater for serial search than for parallel search. These results do not support strong versions of attentional window theory, which claim that capture by any salient stimulus requires parallel search. Instead, abrupt onsets and color singletons seem to be oppositely affected by search mode. The results are roughly consistent with weak versions of attentional window theory, which adds the provision that abrupt onsets are an exception and can capture attention even under a serial search. The present findings also argue against the strong claim that, under parallel search, attentional capture is driven only by bottom-up salience. We found that relevant cues produced much greater capture effects than irrelevant cues, even under parallel search.

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Table 1. Mean Response Times (RTs) in milliseconds and percentage of errors (PEs) as a function of cue color (relevant vs. irrelevant color), search mode (parallel vs. serial) and cue validity (valid vs. invalid) for Experiment 1. Validity effects were calculated as invalid minus valid. Asterisks indicate cue validity effects significantly greater than zero (p < .05).

		Valid		Invalid		Validity Effect	
Trial type		RT	PE	RT	PE	RT	PE
Serial							
	Relevant	615	7.6%	692	11.6%	77*	4.0%
	Irrelevant	667	11.3%	676	10.9%	9	-0.4%
Parallel							
	Relevant	486	5.5%	549	8.8%	63*	3.3%
	Irrelevant	511	6.0%	538	8.4%	27*	2.4%

Table 2. Mean Response Times (RTs) in milliseconds and percentage of errors (PEs) as a function of cue color (target vs. non-target color), search mode (parallel vs. serial) and cue validity (valid, invalid, vs. absent) for Experiment 2. Validity effects were calculated as invalid minus valid. Asterisks indicate cue validity effects significantly greater than zero (p < .05).

		Valid		Invalid		Absent		Validity Effect	
Trial type		RT	PE	RT	PE	RT	PE	RT	PE
Serial						568	9.3%		
	Relevant	533	6.6%	590	8.9%			57*	2.2%
	Irrelevant	567	8.8%	576	9.5%			9	0.8%
Parallel						538	7.2%		
	Relevant	513	6.0%	561	8.9%			48*	2.9%
	Irrelevant	525	7.4%	549	7.5%			24*	0.1%

Table 3. Mean response times (RTs) in milliseconds and percentage of errors (PEs) as a function of setsize (4 vs. 8), search mode (parallel vs. serial) and cue validity (valid, invalid, vs. absent) for Experiment 3. Validity effects were calculated as invalid minus valid. Asterisks indicate cue validity effects significantly greater than zero ($p < .05$).

	Valid		Invalid		Absent		Validity Effect	
Trial type	RT	PE	RT	PE	RT	PE	RT	PE
Setsize 4								
Parallel	532	5.1%	562	7.0%	554	5.3%	30*	1.9%
Serial	608	6.2%	642	7.6%	629	6.0%	34*	1.4%
Setsize 8								
Parallel	551	5.8%	590	7.0%	584	6.8%	38*	1.3%
Serial	672	8.7%	725	10.4%	712	9.3%	53*	1.7%

Table 4. Mean response times (RTs) in milliseconds and percentage of errors (PEs) as a function of search mode (parallel vs. serial) and cue validity (valid vs. invalid) for Experiment 4. Validity effects were calculated as invalid minus valid. Asterisks indicate cue validity effects significantly greater than zero (p < .05).

	Valid		Invalid		Absent		Validity Effect	
Trial type	RT	PE	RT	PE	RT	PE	RT	PE
Serial	576	9.7%	604	10.1%	586	10.4%	28*	0.4%
Parallel	529	8.5%	539	7.9%	532	7.6%	10*	0.6%

Table 5. Mean response times (RTs) in milliseconds and percentage of errors (PEs) as a function of search mode (parallel vs. serial) and set-size (4 vs. 8) for Experiment 5. Search slopes were calculated as setsize 8 minus setsize 4 and then divided by four.

	4		8		
Trial type	RT	PE	RT	PE	Search Slope
Parallel	507	8.1%	542	9.0%	8.6
Serial	561	9.0%	638	10.6%	19.2

Table 6. Mean cue validity effects (invalid minus valid) in milliseconds as a function of search mode (parallel vs. serial) and cue type (relevant and irrelevant) for the pooled data of Experiment 1 and 2.

	Relevant	Irrelevant		
	Orange	Yellow & Red	Blue & Green	All
Parallel	54.9	37.2	14.3	25.7
Serial	66.6	16.7	-0.5	8.1

Figure Captions

Figure 1. Examples of cues and search displays from Experiment 1 and Experiment 2. In Experiment 1, a setsize of 8 was used. In Experiment 2, a setsize of 4 was used, similar to previous pre-cuing experiments (cf., Folk et al. 1992). Note: there was also a frame between the cue and search array, consisting of empty boxes, as in pre-cuing studies (see the methods section for more details).

Figure 2. Cue validity effects for relevant and irrelevant color singletons by search condition in Experiments 1 and 2. Bars represent the standard error of the mean.

Figure 3. Examples of cues and search displays from Experiment 3 and Experiment 4. In Experiment 3, two different setsizes (4 and 8) were used and the cue appeared before the search array. In Experiment 4, the cue appeared within the search display (0-ms SOA) similar to many irrelevant feature paradigms with abrupt onsets (cf., Jonides & Yantis, 1988).

Figure 4. Cue validity effects for irrelevant abrupt onsets by search condition and setsize in Experiments 3 and 4. Bars represent the standard error of the mean.

Figure 1

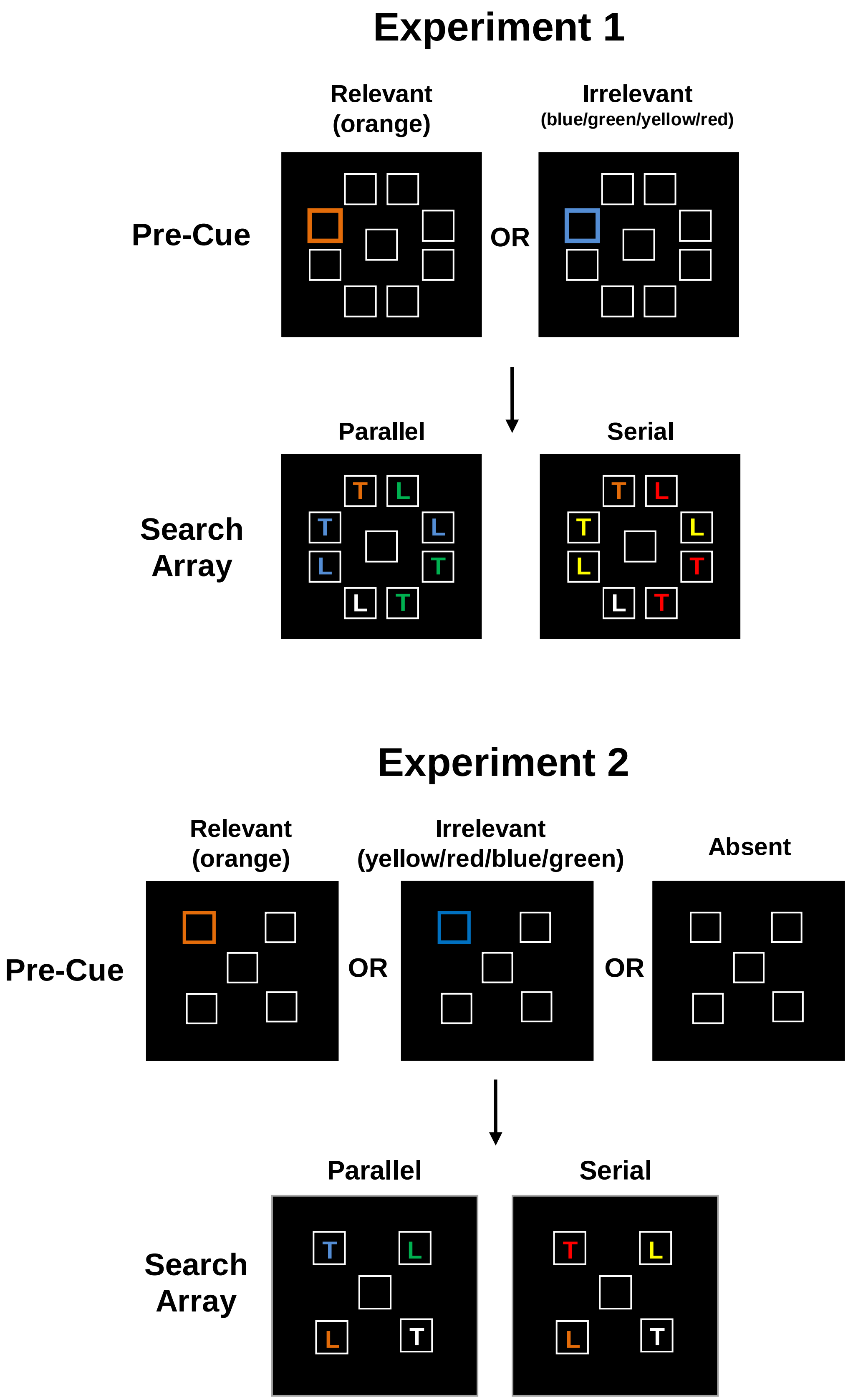
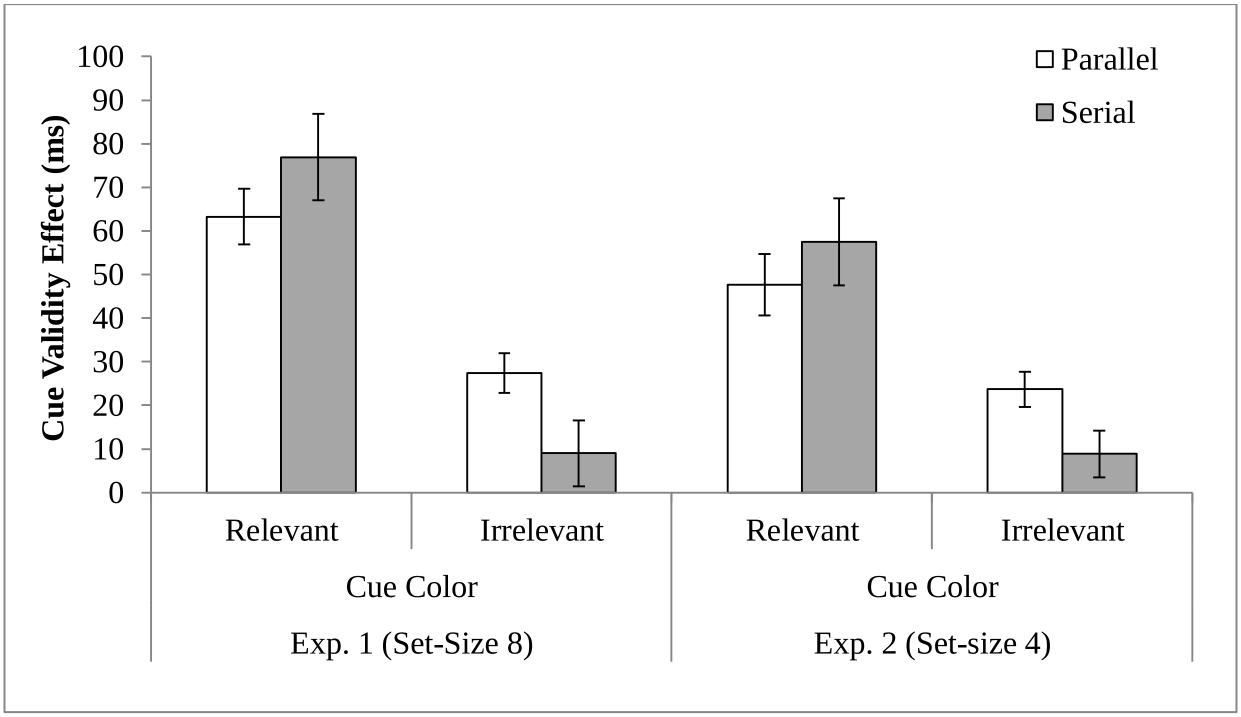

Experiment 1
Relevant
(orange)
Irrelevant
(blue/green/yellow/red)
Pre-Cue
OR
Parallel
Serial
Search
Array
T
L
T
L
L
T
L
T
T
L
T
L
L
T
L
T
Experiment 2
Relevant
(orange)
Irrelevant
(yellow/red/blue/green)
Absent
Pre-Cue
OR
OR
Parallel
Serial
Search
Array
T
L
L
T
T
L
L
T

Figure 2.



Parallel
Serial
Cue Validity Effect (ms)
100
90
80
70
60
50
40
30
20
10
0
Relevant
Irrelevant
Relevant
Irrelevant
Cue Color
Cue Color
Exp. 1 (Set-Size 8)
Exp. 2 (Set-size 4)

Figure 3.

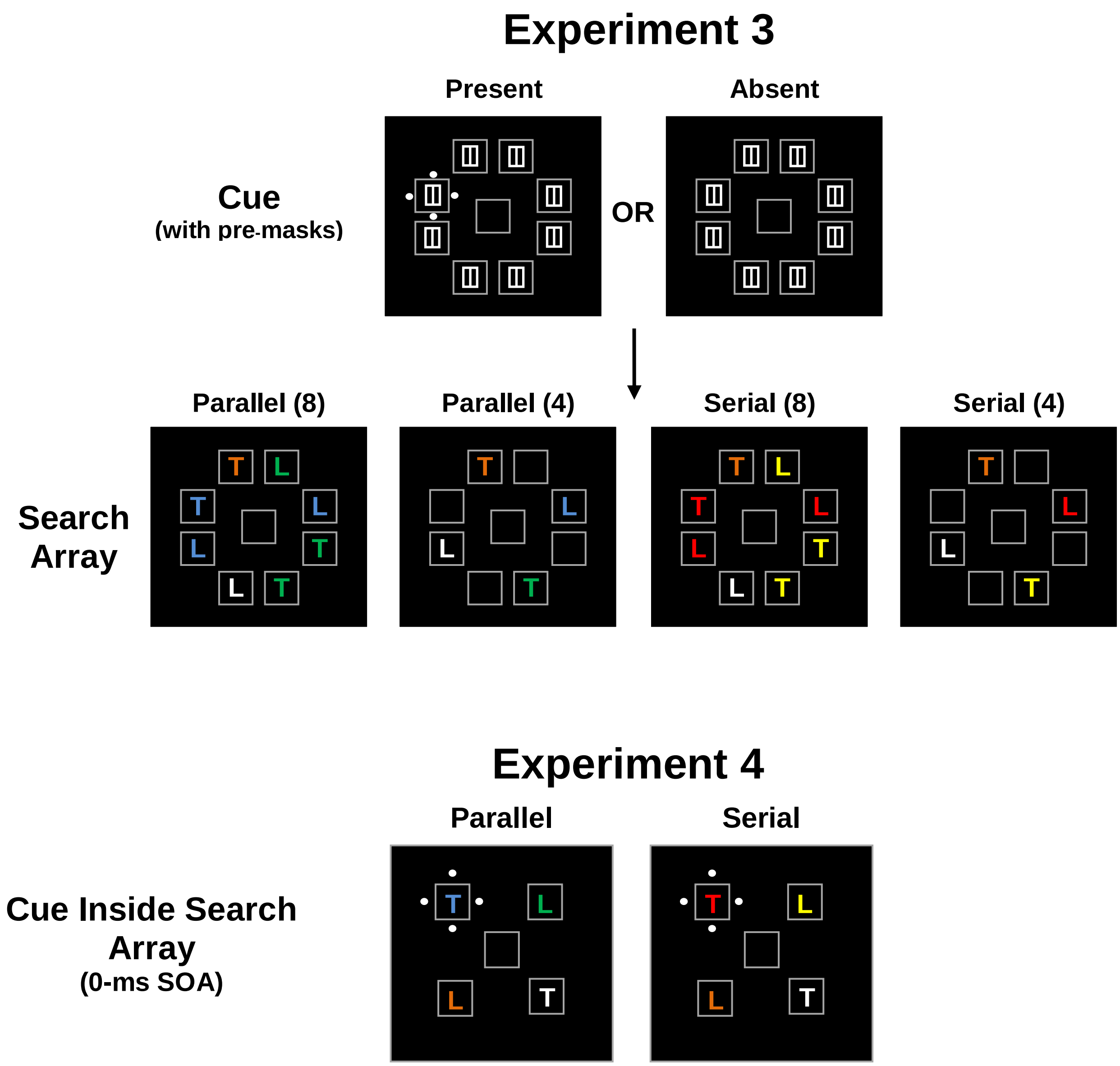
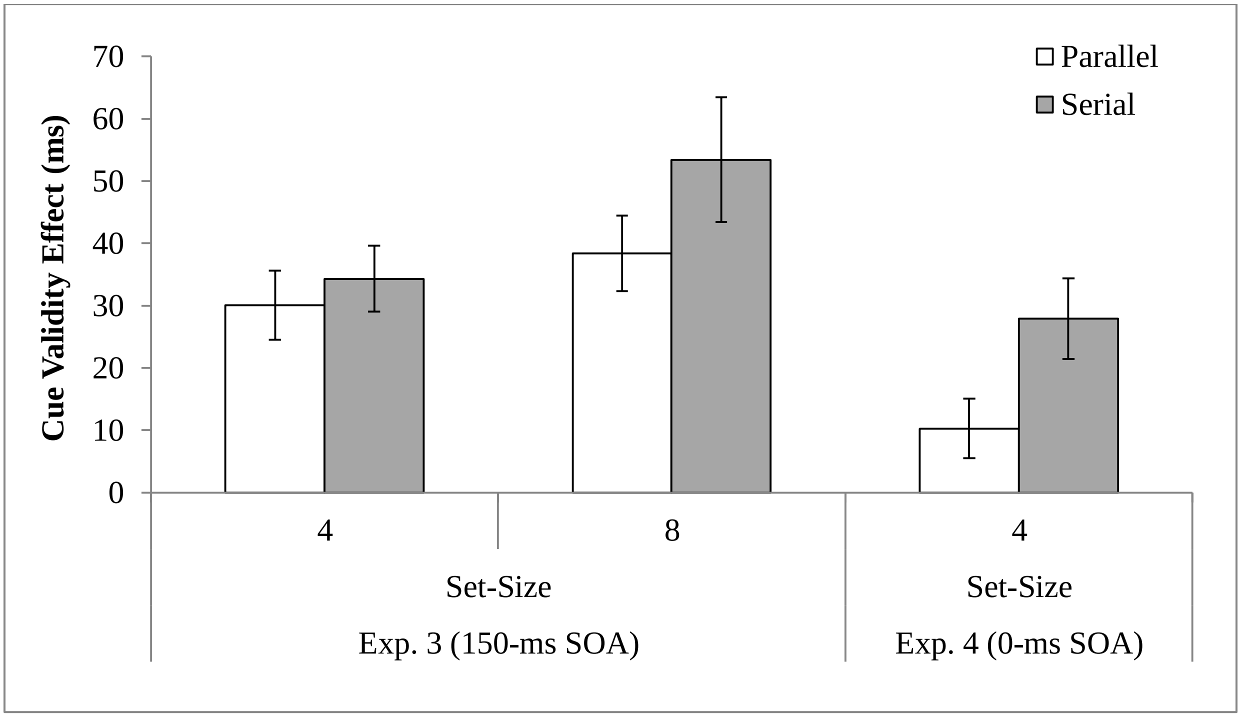

Experiment 3
Present
Absent
Cue
(with pre-masks)
OR
Parallel (8)
Parallel (4)
Serial (8)
Serial (4)
Search
Array
Experiment 4
Parallel
Serial
Cue Inside Search
Array
(0-ms SOA)

Figure 4.


Parallel
Serial
Cue Validity Effect (ms)
70
60
50
40
30
20
10
0
4
8
4
Set-Size
Set-Size
Exp. 3 (150-ms SOA)
Exp. 4 (0-ms SOA)